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(54) **Semiconductor accelerometer.**

(57) A semiconductor accelerometer includes a package containing damping liquid. A base is fixedly disposed within the package. A semiconductor plate is disposed within the package and is supported on the base. The semiconductor plate has a movable free end and a deformable diaphragm. A semiconductor strain gauge is associated with the diaphragm and deforms in accordance with deformation of the diaphragm. The base has a first surface opposing the semiconductor plate free end. The first surface of the base has a recess for limiting movement of the semiconductor plate free end. The recess extends to and opens at a second surface of the base which differs from the first surface.

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FIG. 1

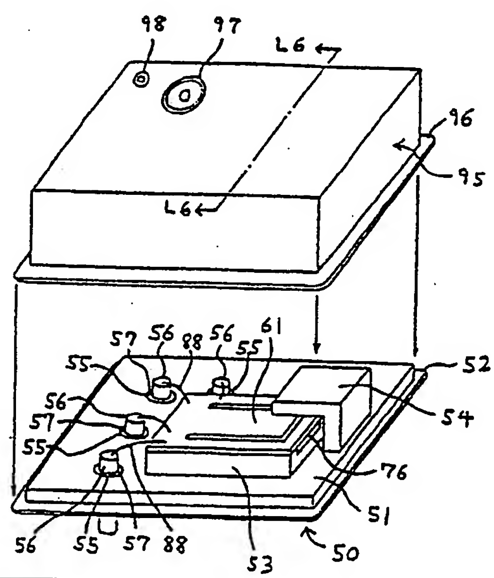

Fig. 5 is a perspective view of the stopper of Fig. I.

Fig. 6 is a sectional view of the assembled accelerometer taken along the line L6-L6 of Fig. I.

Fig. 7 is a perspective view of a first modified base in the first embodiment of this invention.

Fig. 8 is a perspecitve view of a second modified base in the first embodiment of this invention.

Fig. 9 is a perspective view of a modified stopper in the first embodiment of this invention.

Fig. I0 is a perspective view of the cantilever free end of Figs. I-3.

Fig. II is a sectional view of cantilever free end provided with a mass of a first modified structure in the first embodiment of this invention.

Fig. I2 is a diagram of a portion of the cantilever free end of Fig. II.

Fig. I3 is a plan view of a cantilever free end provided with a mass of a second modified structure in the first embodiment of this invention.

Fig. I4 is a plan view of a cantilever free end provided with a mass of a third modified structure in the first embodiment of this invention.

Fig. I5 is a sectional view of a semiconductor accelerometer according to a second embodiment of this invention.

Fig. I6 is a plan view of a portion of a cantilever in a semiconductor accelerometer according to a third embodiment of this invention.

Fig. I7 is a schematic diagram of the semiconductor accelerometer of Fig. I6 and an electrical circuit.

Fig. I8 is a plan view of a modified cantilever in the third embodiment of this invention.

Fig. I9 is a schematic diagram of a semiconductor accelerometer and an electrical circuit according to a fourth embodiment of this invention.

Fig. 20 is a diagram showing the relationship between acceleration and output of the absolute value circuit of Fig. I9.

Fig. 2I is a perspective view of a semiconductor accelerometer sensor chip, a jig, and parts.

Fig. 22 is a sectional view of a semiconductor accelerometer according to a fifth embodiment of this invention.

Fig. 23 is a top view of the cantilever of Fig. 22.

Fig. 24 is a graph showing the theoretical and experimental relationships between the value "dx/h" and the value "fc/fc0" in the semiconductor accelerometers of Figs. 22 and 23.

DESCRIPTION OF THE FIRST PREFERRED EMBODIMENT

Fig. I shows a semiconductor accelerometer according to a first embodiment of this invention. It should be noted that in Fig. I, a package is disassembled to show an internal structure. As shown in Fig. I, the semiconductor accelerometer includes a stem or lower package member 50 made of metal such as Kovar. The stem 50 has a raised portion 5I surrounded by lowered edges 52. The stem 50 is formed by a suitable process such as a pressing process. For example, during fabrication of the stem 50, edges of a plate-shaped material are pressed into lowered edges 52 and simultaneously a raised portion 5I is formed on the material.

A base 53 and a stopper 54 are fixedly mounted on the raised portion 5I. For example, the base 53 and the stopper 54 are soldered to the raised portion 5I. Four holes 55 extend through walls of the raised portion 5I. Terminals 56 extend through the respective holes 55. The terminals 56 are fixed to the walls of the raised portion 5I by hard glasses 57 in the holes 55. The hard glasses 57 surround the respective terminals 56 so that the terminals 56 are electrically insulated from the walls of the raised portion 5I. The hard glasses 57 hermetically extend between the terminals 56 and the walls of the raised portion 5I.

An acceleration sensor element 60 includes a cantilever 6I supported on the base 53. The cantilever 6I is composed of a semiconductor plate such as an n-type silicon single crystal plate.

As shown in Figs. 2 and 3, the cantilever 6I includes a base end or support 62, a free end 63, and a thin diaphragm 64 extending between the support 62 and the free end 63. A guard 65 integrally extending from the support 62 surrounds the free end 63 to protect the latter. The guard 65 is spaced from the free end 63 and the diaphragm 64 by a gap 66. It should be noted that the guard 65 may be omitted.

A scribe alley for producing the gap 66 is created by etching both surfaces of a semiconductor starting material for the cantilever 6I. For example, after the upper surface of a portion of the starting material to be scribed is subjected to etching, the lower surface of the portion is subjected to etching during the formation of the diaphragm 64.

Lower surfaces of given areas of the support 62 and the guard 65 are coated with layers 70 containing solderable metal such as nickel. The formation of the solderable layers 70 is performed by plating or vapor coating. Upper surfaces of given areas of the base 53 are correspondingly coated with layers 7I of solderable metal which

and 96. In this way, the shell 95 and the stem 50 form a sealed package or casing which accommodates the base 53, the sensor element 60, and the stopper 54.

The top walls of the shell 95 has holes 97 and 98. The hole 97 allows damping liquid to be injected into the package. The hole 98 allows escape of air from the package during injection of damping liquid into the package. After the shell 95 and the stem 50 are welded, as shown in Fig. 6, an outlet needle of an injector 100 is inserted into the package via the hole 97 and a predetermined quantity of damping liquid 101 is injected into the package by the injector 100. For example, the damping liquid 101 fills 70-80% of the volume of the interior of the package. During the injection of the damping liquid 101, the hole 98 allows air to escape from the package. After the injection of the damping liquid 101 into the package is completed, the holes 97 and 98 are sealingly closed by solder. As shown in Fig. 6, a predetermined volume of air 105 remains within the package.

A partition wall 102 extending within the package is attached to the top wall of the shell 95. A gap between the partition wall 102 and the stem 100 allows movement of the damping liquid 101 between chambers divided by the partition wall 102. The partition wall 102 prevents the damping liquid 101 from being choppy.

As described previously, the area of the base 53 opposing the cantilever 61 is formed with the recess 76 of the predetermined depth. In the case where the cantilever free end 63 is diplaced toward the base 53 by a shock applied to the accelerometer, when the free end 63 meets the bottom surface of the recess 76, the free end 63 is forcedly stopped. Accordingly, the depth of the recess 76 determines the maximal downward displacement of the cantilever free end 63. The depth of the recess 76 is chosen to prevent excessive displacement of the cantilever 61 which would damage the cantilever 61.

As described previously, the recess 76 extends between the side surfaces 77 and 78 of the base 53 and opens at the side surfaces 77 and 78. Accordingly, during displacement of the cantilever 61 toward the base 53, the damping liquid 101 freely escapes from the recess 76 via open ends of the recess 76 located at the side surfaces 77 and 78 of the base 53. The free escape of the damping liquid 101 from the recess 76 ensures that effective viscosity of the damping liquid 101 fixing resistance to movement of the cantilever 61 is essentially determined by only the intrinsic damping factor of the damping liquid 101. In this way, the cantilever 61 is prevented from undergoing excessive damping effect so that excellent frequency characteristics of the accelerometer are available. Specifically, the resonance of the cantilever 61 is reliably prevented from adversely affecting characteristics of the accelerometer, and a wide frequency range where the accelerometer operates acceptably is obtained.

The stopper 54 limits upward displacement of the cantilever 61 and prevents damage to the cantilever 61 which would be caused by exessive displacement of the cantilever 61. The upper plate 93 of the stopper 54 extends above only the distal edge of the cantilever free end 63. In other words, a major part of the cantilever 61 except the distal edge of the free end 63 is uncovered from the stopper 54. Accordingly, the stopper 54 does not increase effective viscosity of the damping liquid 101 so that acceptable frequency characteristics of the accelerometer are ensured.

Fig. 7 shows a first modified base 53 having an upper surface formed with a recess 76, which extends to and opens at one side surface 78 of the base 53.

Fig. 8 shows a second modified base 53 having an upper surface formed with a recess 76, which has a cross shape and which extends to and opens at four side surfaces of the base 53.

Fig. 9 shows a modified stopper 54 which is composed of a hook-shaped combination of plates 91 and 93 extending perpendicular and parallel to the raised portion 51 of the step 50 (see Fig. 1) respectively.

The metal layers 80 and the solder layers 81 will be described in more detail hereinafter with reference to Figs. 2, 3, and 10. It is preferable that the metal layers 80 and the solder layers 81 are formed on a wafer of a single crystal of silicon to increase the productivity. It should be noted that in Fig. 10 and the related description, the silicon wafer is illustrated and explained as the cantilever free end 63 for a better understanding.

During fabrication of the metal layers 80 and the solder layers 81, a film of resist defining metal layer patterns is formed on the surface of the cantilever free end 63 by use of a glass mask, and then titanium, nickel, and gold are sequentially deposited on the surface of the cantilever free end 63 by vapor coating to form the metal layers 80. In this process, titanium may be replaced by chromium. After the metal layers 80 are completed, the resist film is removed.

As shown in Figs. 2, 3, and 10, the metal layers 80 have identical rectangular shapes, extending parallel to each other. The metal layers 80 are spaced at regular intervals along the longitudinal direction "x" of the cantilever free end 63. The longitudinal axis of each metal layer 80 extends perpendicular to the longitudinal direction "x" of the cantilever free end 63 and thus parallel to the lateral direction "y" of the cantilever free end 63. The lateral edges of each metal layer extend in-

DESCRIPTION OF THE SECOND PREFERRED EMBODIMENT

Fig. I5 shows a semiconductor accelerometer according to a second embodiment of this invention which includes a beam whose opposite ends are fixed. As shown in Fig. I5, the beam includes a silicon substrate I20 having a diaphragm I2I. Semiconductor strain gauges I22 are formed in the diaphragm I2I. The semiconductor strain gauges I22 are electrically connected to terminals I24 via wiring layers I23 which are formed in the silicon substrate I20 by high-density diffusion of p-type impurities. The upper surface of the silicon substrate I20 is coated with an insulating layer I25. Solder layers I27 are fixed via solderable metal layers I26 on the areas of the insulating layer I25 which extend directly above the diaphragm I2I but which reside outside the regions directly above the semiconductor strain gauges I22. The solder layers I27 form a mass or weight fixed to the diaphragm I2I. The configuration of the solder layers I27 is of a point symmetry with respect to the center of the diaphragm I2I.

DESCRIPTION OF THE THIRD PREFERRED EMBODIMENT

Figs. I6 and I7 show a semiconductor accelerometer according to a third embodiment of this invention, which is similar to the embodiment of Figs. I-6 except for design changes described hereinafter.

As shown in Fig. I6, semiconductor strain gauges 85AB, 85BD, 85AC, and 85CD formed in the cantilever diaphragm 64 extend symmetrically. Specifically, the strain gauges 85AB and 85CD are symmetrical with respect to the central longitudinal axis of the cantilever 6I. The strain gauges 85BD and 85AC are symmetrical with respect to the central longitudinal axis of the cantilever 6I. One end of the strain gauge 85AB is connected to one end of the strain gauge 85BD via a wiring layer 86B. The other end of the strain gauge 85AB is connected to one end of the strain gauge 85AC via a wiring layer 86A and a wiring member 87A. The other end of the strain gauge 85BD is connected to one end of the strain gauge 85CD via a wiring member 87D and a wiring layer 86D. The other end of the strain gauge 85AC is connected to the other end of the strain gauge 85CD via a wiring layer 86C. The wiring layers 86A-86D lead to the pads A-D (see Fig. 2) via the wiring members 87A-87D respectively.

The wiring layers 86B and 86C extend from the cantilever diaphragm 64 into the cantilever free end 63, returning to the cantilever diaphragm 64 and extending into the cantilever support 62 via the cantilever diaphragm 64. Accordingly, in cases where the cantilever diaphragm 64 breaks along a transverse line, the wiring layers 86B and 86C snap. The breaks of the wiring layers 86B and 86C cause abnormal output of the strain gauge bridge circuit.

As shown in Fig. I7, a preset constant potential Vcc is applied to the pad or point B via a resistor R0. The pad or point D is grounded. The pad or point C is grounded via a resistor R5 having a resistance equal to the resistance of the resistor R0. A constant current passes through the pad or point A.

A combination of an operational amplifier AMPI and resistors RI and R2 constitutes a non-inverting amplifier E. A combination of an operational amplifier AMP2 and resistors R3 and R4 constitutes a non-inverting amplifier F. A first input terminal of the amplifier E is connected to the point C. A second input terminal of the amplifier E is grounded. A first input terminal of the amplifier F is connected to the point B. A second input terminal of the amplifier F is connected to an output terminal of the amplifier E. The resistance of the resistor RI is equal to the resistance of the resistor R4. The resistance of the resistor R2 is equal to the resistance of the resistor R3. The resistances of the resistors R0 and R5 are much greater than the resistances of the strain gauges 85AB, 85AC, 85BD, and 85CD.

When the strain gauge bridge circuit and the electrical connections to the bridge circuit are normal, a voltage output Vout from the amplifier F is given by the following equation.

$$Vout = (VB - VC)\bullet(rl + r2)/r2$$

where the characters VB and VC represent potentials at the points B and C respectively, and the characters rl and r2 represent the resistances of the resistors RI and R2 respectively. It should be noted that the resistances of the resistors R3 and R4 are equal to the resistances of the resistors R2 and RI respectively.

In cases where the wiring layers 86B and 86C break due to a damage to the cantilever diaphragm 64, the potential VB becomes equal to the preset constant potential Vcc and the potential VC drops to the ground potential so that the voltage output Vout considerably rises above its normal value. Accordingly, a damage to the cantilever diaphragm 64 can be detected by sensing a considerable rise in the voltage output Vout.

are formed on longitudinal edges of the sensor chip 311. For example, the metal layers 311a are composed of films of nickel and gold formed by vapor coating.

The sensor chip 311 is placed on the upper surface of the small base 310b in such a manner that the metal layers 311a face upward and that side surfaces of the sensor chip 311 contact the side walls 310c and 310d. Solder foils 312 are placed on the metal layers 311a.

A base 313 has a recess 313a extending between opposite end surfaces. The base 313 serves to limit upward displacement of the cantilever free end 311e. The base 313 is made of material having a thermal expansion coefficient similar to the thermal expansion coefficient of the material forming the sensor chip 311. In the case where the sensor chip 311 is made of silicon, the base 313 is also made of silicon. The surface of the base 313 having the recess 313a is placed on the solder foils 312 and is provided with solderable metal layers similar to the metal layers 311a. Side surfaces of the base 313 contact the side walls 310c and 310d. A solder foil 312a is placed over an upper surface of the base 313.

An L-shaped stopper 314 serves to limit downward displacement of the cantilever free end 311e. The stopper 314 is placed on a lower wall 310e of the jig 310 defining the cut 310a. When the stopper 314 is placed in position, a lower portion of the stopper 314 contacts the small base 310b. The stopper 314 is made of metal such as Kovar. A solderable metal layer 314a is formed on an upper surface of the stopper 314. For example, the matal layer 314a is composed of films of nickel and gold formed by a plating process. A solder foil 312b is placed on the metal layer 314a.

A base plate 315 serves to carry the base 313. In the case where the semiconductor accelerometer is disposed within a package including a combination of a metal cap and a metal base, the base plate 315 corresponds to the metal base. Poles 315a attached to the base plate 315 serve to fix the base plate 315. Specifically, when the poles 315a are inserted into respective holes 310f in the jig 310, the base plate 315 is fixed in position. Poles 315b attached to the base plate 315 serve to fix the sensor chip 311. The areas of the surface of the base plate 315 opposing the base 313 and the stopper 314 are provided with solderable metal layers.

After the parts are placed in positions along directions as viewed in Fig. 21, the jig 310 is inverted through 180°. When the jig 310 is inverted, the sensor chip 311, the base 313, and the base plate 315 are subjected to suitable pressures by their own weights. Accordingly, the parts are prevented from undergoing excessive pressures which could cause damages. The inverted jig 310 is heated and the solders are exposed to a reflowing process in a furnace filled with hydrogen gas. The reflowing process allows the sensor chip 311, the base 313, the base plate 315, and the stopper 314 to be connected. In this way, the parts are soldered at the same time so that assembly of the accelerometer is simple. Exposure of the solders to a single reflowing process ensures reliable connections between the parts.

It should be noted that the step of inverting the jig 310 may be omitted. The solders may be replaced by adhesives made of suitable material such as resin. The solder layers 311b on the cantilever free end 311e may be replaced by a mass made of Kovar or glass fixed to the cantilever free end 311e with solder or adhesive.

DESCRIPTION OF THE FIFTH PREFERRED EMBODIMENT

In general, the semiconductor accelerometer of Figs. 1-6 has frequency characteristics such that the output level of the accelerometer remains essentially flat below a cut-off frequency fc and decreases rapidly above the cut-off frequency fc. Accordingly, the accelerometer is usable in a frequency range below the cut-off frequency fc.

A fifth embodiment of this invention is similar to the embodiment of Figs. 1-6 except for specific settings described hereinafter. The fifth embodiment will be described with reference to Figs. 22 and 23.

The following description is made with respect to cases where an acceleration to be measured is applied only to the base 53.

According to experiments, it was found that the cut-off frequency fc is expressed as follows.

$$fc = k1/[DSdx(1 + k2dx/h)]$$
$$= fc0/[1 + (k2dx/h)]$$

where the characters k1 and k2 denote constants; the character D denotes the viscosity of the damping liquid; the character S denotes the area of the cantilever free end 63 which equals the length A multiplied by the width B (see Figs. 22 and 23); the character dx denotes a displacement of the cantilever free end 63 with respect to an acceleration of 1 G (see Fig. 22); the character h denotes the normal distance between the bottom surface of the recess 76 and the weights or solder layers 81 (see Fig. 22); and the character fc0 denotes a cut-off frequency defined in a free area in the damping liquid without a structure limiting displacement of the cantilever free end 63.

(a) a package containing damping liquid;

(b) a base fixedly disposed within the package;

(c) a cantilever disposed within the package and supported on the base, the cantilever having a movable free end and a deformable diaphragm; and

(d) a semiconductor strain gauge associated with the diaphragm and deforming in accordance with deformation of the diaphragm; and

(e) a wall disposed within the package, the wall being spaced from the cantilever free end by a predetermined distance and allowing displacement of the cantilever free end in a range corresponding to the predetermined distance;

wherein the predetermined distance is equal to or greater than a value h given by the following equation;

h = dxKfc/(fc0-fc)

where the character dx denotes a displacement of the cantilever free end with respect to an acceleration of 1 G; the character fc denotes a desired cut-off frequency; the character fc0 denotes a cut-off frequency in a free area in the damping liquid without the wall; and the character K denotes a constant.

10. An accelerometer comprising:

(a) a cantilever moving in accordance with an applied acceleration and immersed in damping liquid;

(b) a strain gauge associated with the cantilever and moving in accordance with movement of the cantilever;

(c) a member having a recess into which the cantilever is movable, and

(d) means for allowing the damping liquid to essentially freely escape from the recess when the cantilever moves into the recess.

11. The accelerometer of claim 9 further comprising a mass fixed to the cantilever, the mass comprising separate layers of solder fixed on the cantilever.

FIG. 2

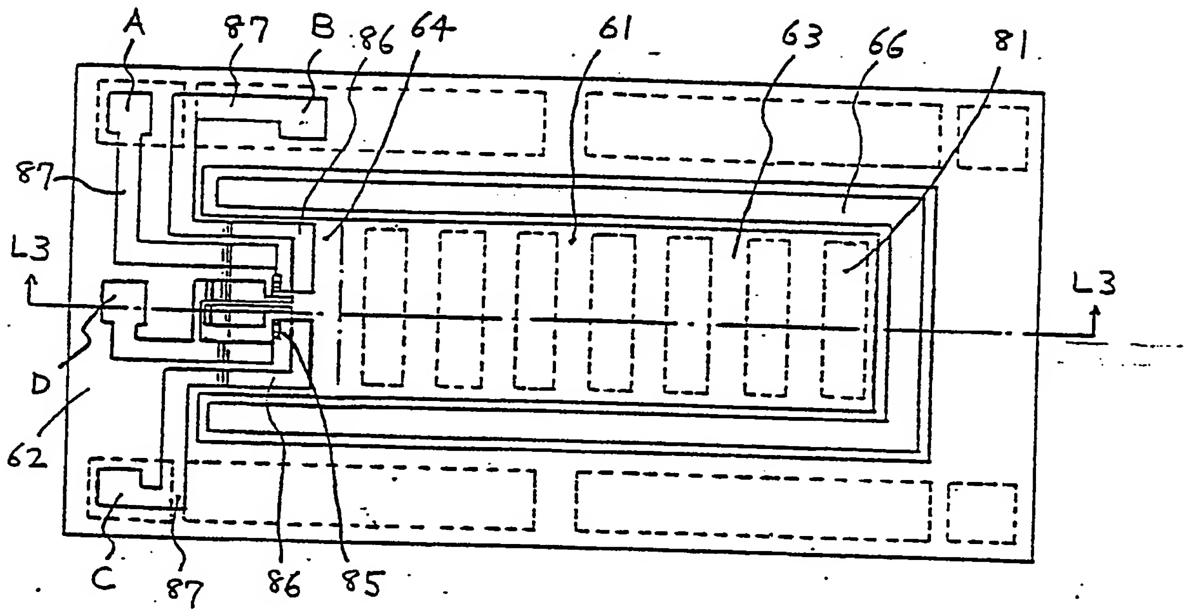
A
87
B
86
64
61
63
66
81
L3
L3
D
62
C
87
86
85

FIG. 3

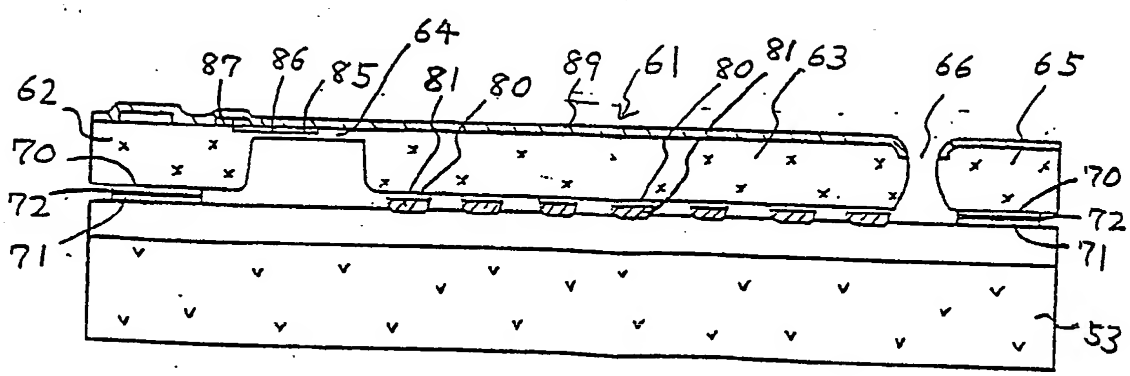
64
87
86
85
81
80
89
61
80
81
63
66
65
62
70
72
71
70
72
71
53

FIG. 6

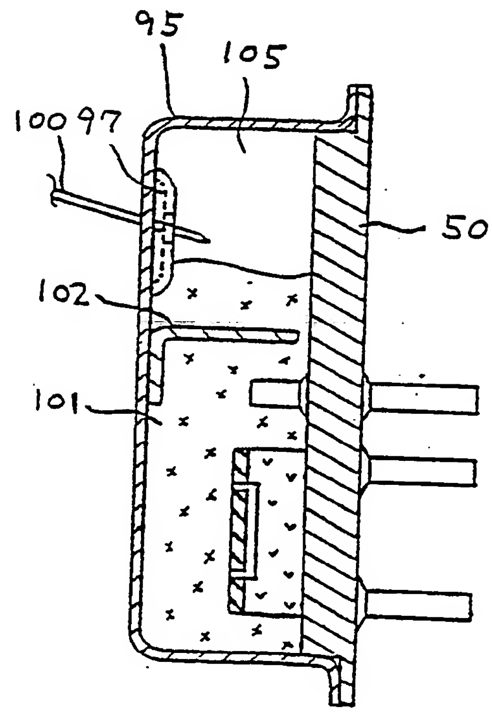

FIG. 14

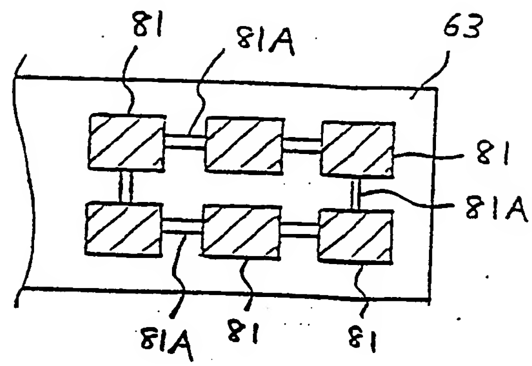

FIG. 15

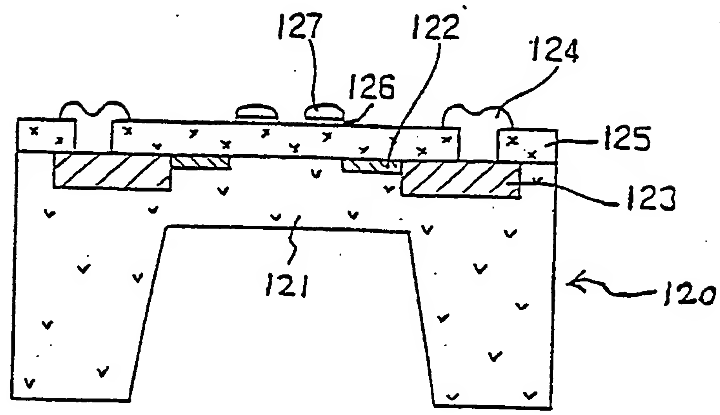

FIG. 17

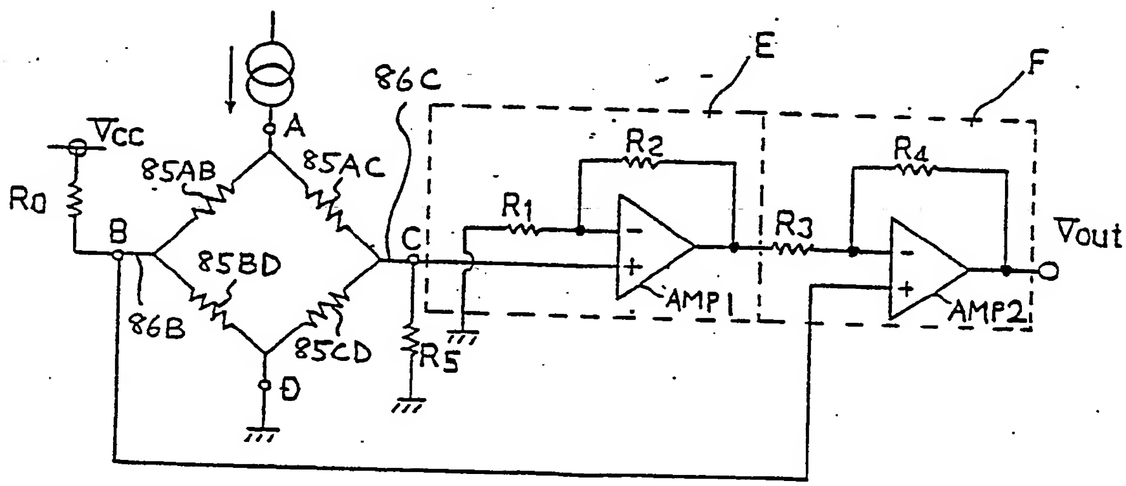
86C
E
F
Vcc
A
85AB
85AC
R2
R4
R0
R1
R3
Vout
B
C
85BD
AMP1
AMP2
86B
85CD
R5
D

FIG. 19

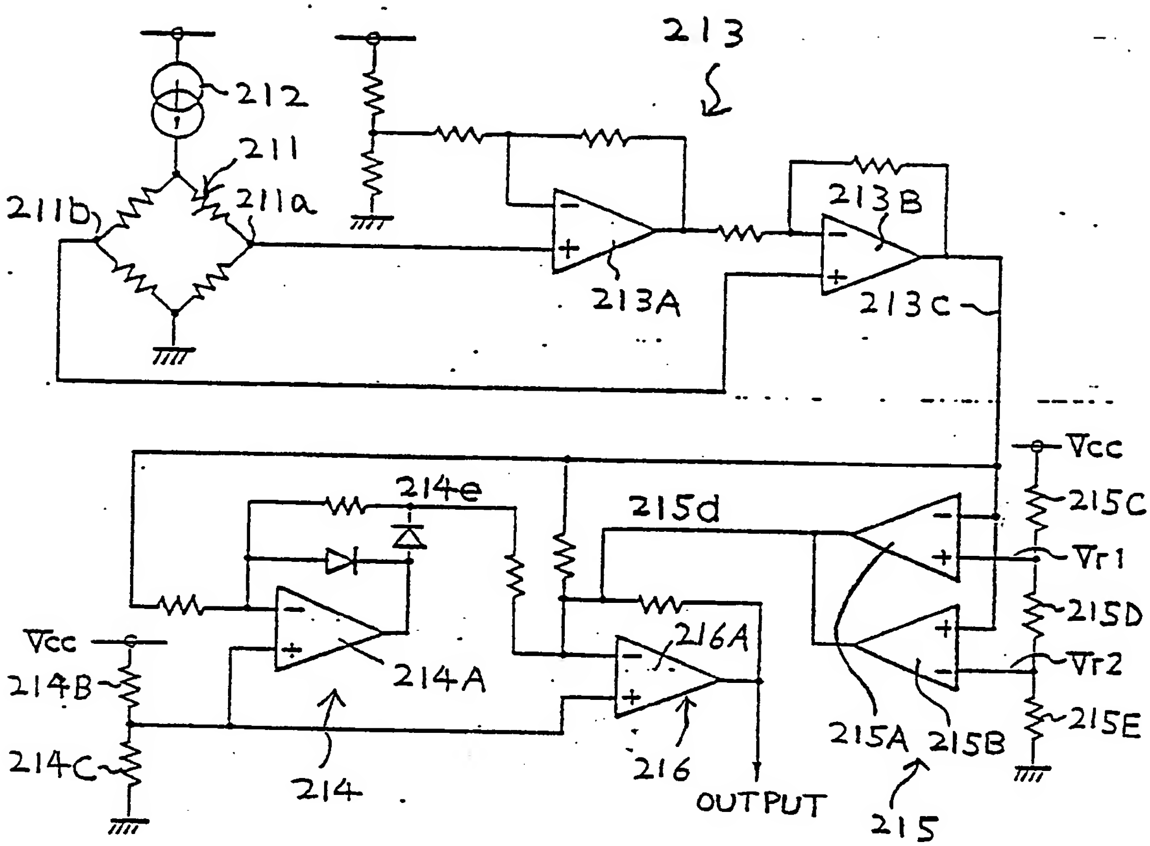
213
212
211
211b
211a
213B
213A
213c
Vcc
215C
214e
215d
Vr1
215D
216A
Vcc
214A
Vr2
214B
215E
215A
215B
214C
214
216
OUTPUT
215

FIG. 20

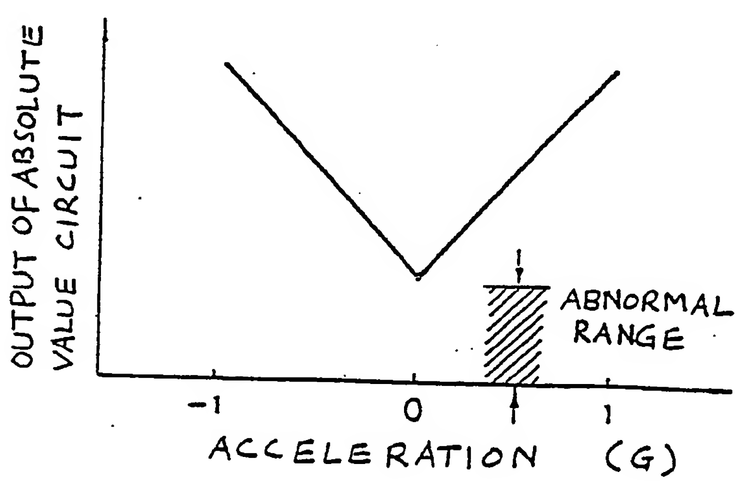
OUTPUT OF ABSOLUTE VALUE CIRCUIT
ABNORMAL RANGE
-1
0
1
ACCELERATION (G)

FIG. 22

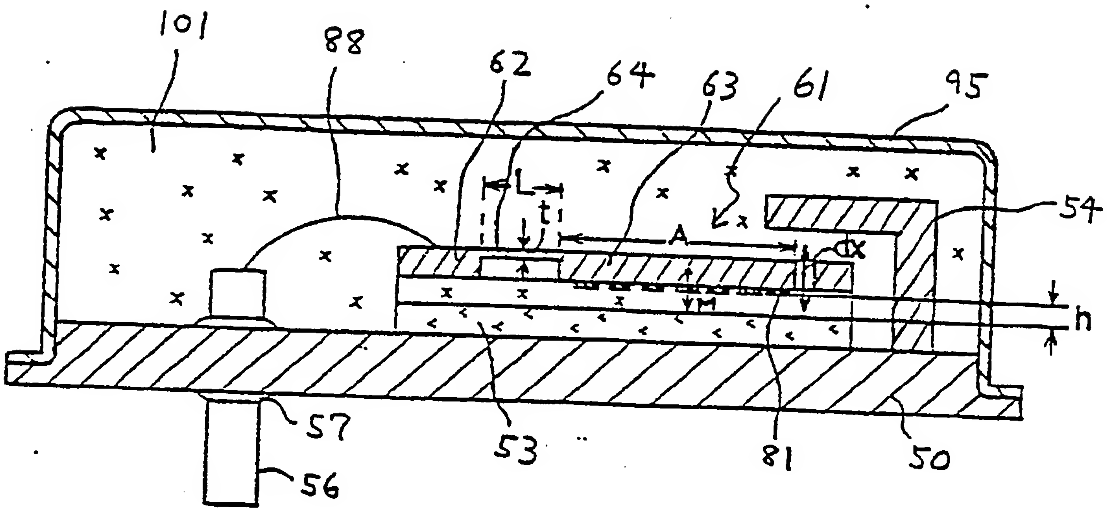

FIG. 23

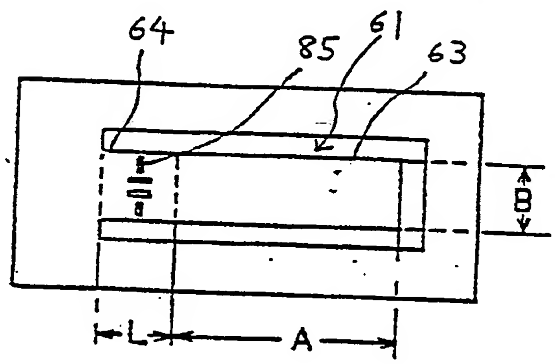

FIG. 24

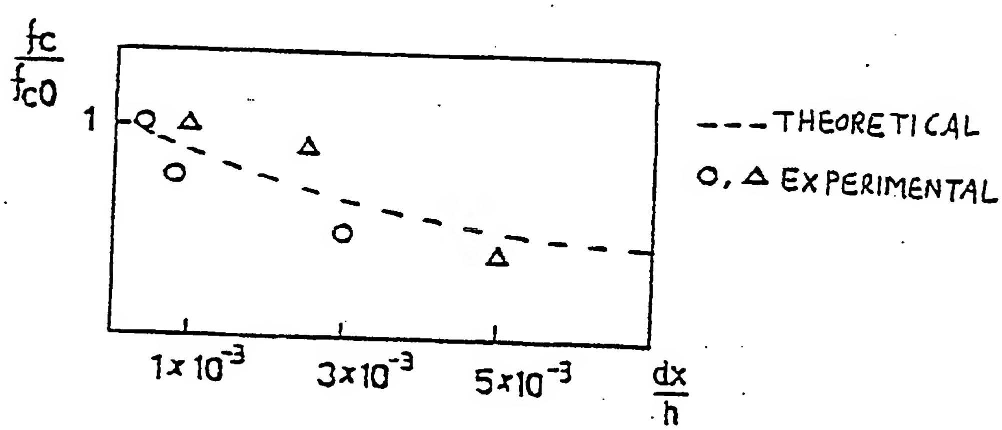

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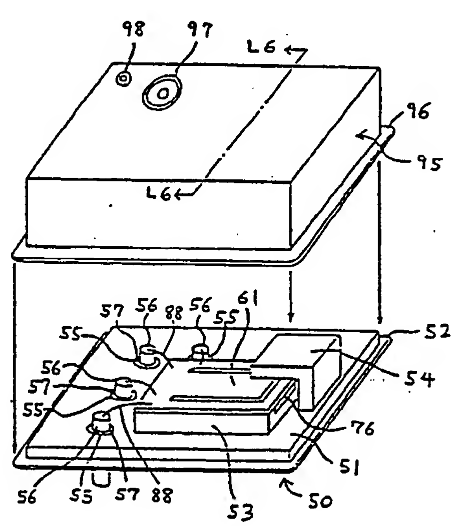
FIG. 1



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